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AN EXPERIMENTAL MICROWAVE IMAGING SYSTEM USING PRE-FORMED BEAMS

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ABSTRACT

An experimental investigation of microwave imaging using preformed beams is made at a frequency of 24 gigahertz (λ= 1.25 cm).

The apparatus consists of a 1.5 meter diameter parabolic reflector with a mosaic of detectors at the focal plane. The detector outputs are amplified and stored to provide a set of d.c. voltages, proportional to the energy received at points in the image plane, to be applied to an intensity modulated display.

Using microwave antenna and optical principles, the theory of image formation and resolution is discussed. The range capability is predicted by the radar range equation, using measured parameters.

Advantages of the system with respect to conventional scanning radar appear for fast moving objects at close range.

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TABLE OF SYMBOLS AND ABBREVIATIONS

A	aperture area
D	aperture diameter
F	focal length
G_r	receiving antenna gain
G_t	transmitting antenna gain
λ	wavelength
P_t	transmitter power
r	range in meters
ρ	aperture efficiency
S	minimum detectable signal
σ	radar cross section

ACKNOWLEDGEMENT

This project was suggested by Professor G. L. Sackman who acted as advisor. Sincere appreciation is expressed for his patience and many hours of helpful discussions.

1. Introduction

A high resolution radar that produces an azimuth-elevation picture would be a significant aid in the identification, classification, and tracking of radar targets. The human eye is accustomed to seeing objects in an azimuth-elevation plane and the ability to recognize the outlines or highlights of an object presented in this plane is natural. An operator must be trained to visualize objects in other planes in order to recognize them readily, especially complicated objects.

One way to implement an azimuth-elevation presentation is to rapidly scan an object in the horizontal plane, with each sweep across the target progressing downward across the target. The signal received by each sweep across the target in the horizontal plane would be presented as an intensity modulated line across a picture tube. Each successive sweep would add a new line similar to the way a television picture is produced. High sweep speeds and an extremely high transmit pulse repetition frequency or even CW transmission would be required if the viewed object was in rapid motion through the field of view. A pulse length equal to at least the time required to completely scan the field of view might be used, or a pulse train with one pulse per picture element.

Another method is to receive all the picture information at one time by the use of many preformed beams. The information from each beam would be displayed as an individual resolution cell. This system requires separate channels for all beams used, each with its own detector, amplifier, and holding circuit. The display could be accomplished by rapidly sampling the stored output of each beam channel and displaying the individual outputs as dots on a picture tube. The

intensity of each dot would be proportional to the output of the corresponding beam channel. The dot's position would correspond to the spatial position of the beams.

A significant advantage of this type system is evident when the hits-per-scan of the two systems are compared. For the purposes of comparison 900 preformed beams arranged in a 30 x 30 matrix will be assumed. It is further assumed that the entire array be sampled once each 10 milliseconds (100 frames per second). This would require a clock rate of approximately 100 kilohertz. Let an equal pulse repetition frequency be chosen. If the scanning system is capable of scanning the entire 900 cells at that rate with the pulse repetition frequency assumed, each cell will receive approximately 1000 hits per frame of the muliplex display system, compared to 1.1 hits per scan of the conventional radar. Integration of the pulses would occur in the holding circuit. The resulting improvement in signal to noise for integration of one thousand pulses compared to no integration is approximately 12 db as shown in Skolnik [4]. Furthermore, the probability of detecting a rapidly moving target is enhanced. The numbers used in this comparison are considered to be of the order of magnitude required for a useable system.

The purpose of this project was to investigate the practical aspects of implementing a system as described above using many preformed beams to image an object illuminated by a separate microwave transmitter. The system consists of a receiving system made up of a paraboloid reflector with a fixed mosaic of detectors at the focal plane of the reflector. The output of each detector is amplified by its own individual amplifier and applied to a holding circuit. The

voltage in each holding circuit is to be rapidly sampled and displayed as described before. The display system will not be discussed in this paper; the method of producing the video display is treated in a thesis by Lt. A. F. Barta [9].

To the author's knowledge a radar imaging system with an azimuth-elevation display has not been built; however work has been done on similar systems for imaging underwater objects with ultrasonic sound waves. This project could be considered a microwave analog of similar type underwater systems.

Further possible applications not related to imaging might be in situations where large field coverage in azimuth and elevation and high resolution is desired simultaneously. If the spatial position of each beam were known a target could be tracked, probably by a computer, as the target moved from beam to beam. Since range is not a detected parameter in the system discussed, two systems employing triangulation would be required. Range information is possible, however, where the two-way transmission time is long enough that a simultaneous delayed enabling pulse to the amplifier bank is feasible. Such a range gate effectively displays a plane one range cell thick.

Antenna theory pertinent to this project is discussed in Section 2. Also included is a brief discussion of factors influencing system range. Various considerations used in the design of this project are included in Section 3. Section 4 details the experimental procedures and results of tests conducted throughout the project. Theoretical and experimental results are compared. The final section contains concluding remarks and recommendations for improvement of system performance.

2. Theoretical

The basic fundamentals of light and microwave propagation are very similar; therefore, considerations from both fields will be used in the following discussion.

A point object is assumed to scatter spherical waves when illuminated by a microwave source. The wave front appears almost plane at distances much greater than the object diameter. To form an image of this object it is first necessary to collect the plane wave and focus it to a point for detection. A paraboloid, or parabola of revolution, is the most popular and probably easiest device to use for collection and focusing the electromagnetic waves. Consider a uniform wave front arriving at a paraboloid. The individual rays of a plane wave front will be reflected from the surface and focused at a point in the focal plane. If the rays are parallel to the axis of the paraboloid the focal point will lie on the axis. Also, the distance traveled by any ray from a plane perpendicular to the paraboloid axis to the surface and then to the focal point is independent of path. The same would approximately be true if the plane wave front were not perpendicular to the paraboloid axis, provided the angle between the axis and wave front was not too great (generally a few degrees, dependent upon the focal length). The focal point will not lie on the axis but is in a focal plane. Since the path length of all individual rays is equal, the phase is the same and constructive interference occurs at the focal point. A two dimensional drawing illustrating these points is shown in Figure 1.

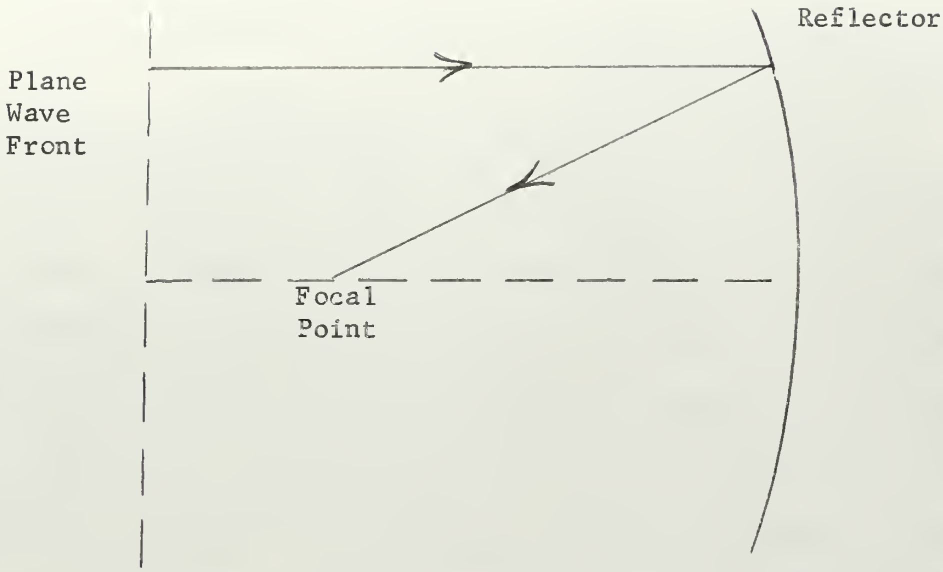


Figure 1. General reflective focusing system

An elementary antenna (feed) is located at the focal point. The pattern of the antenna feed is important when aperture efficiency and side lobe level are considered. Aperture efficiency is proportional to the amount of radiation received by the antenna feed that is intercepted by the reflector. The most efficient aperture illumination is a uniform distribution across the aperture. This is generally not achieved in practice because of the feed pattern and the focal length. For imaging purposes a long focal length ($F/D > 0.5$) is necessary for good directivity off axis. This reduces the efficiency because less energy is intercepted by the reflector; therefore, the feed pattern must be made more directive to achieve good aperture efficiency.

The Fraunhofer diffraction for a clear aperture of a point source in the far field has an intensity pattern of the form $\left(\frac{\sin x}{x}\right)^2$.

The Rayleigh criterion for angular resolution is approximately λ/D radians for a circular clear aperture of diameter D. Feed directivity decreases the resolution.

The feed will also affect the antenna sidelobe pattern due to its position in the focal plane. Since it is placed in front of the reflector the feed effectively blocks or shadows a portion of the aperture. The effect of aperture blocking can be approximated by subtracting the radiation pattern produced by the obstacle from the radiation pattern of the undisturbed aperture. The effect of the obstacle degrades performance by increasing the side lobe level and reducing gain.

The maximum theoretical range may be calculated by use of the basic radar range equation [4]

$$r^4 = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 S}$$

where P_t = transmitter power

G_t = transmitting antenna gain

G_r = receiving antenna gain

λ = wavelength

σ = radar cross section

S = minimum detectable signal

This basic equation does not include the effects of the atmosphere. These effects would be important in the choice of frequencies and signal processing techniques; however, since the purpose of this project is to show feasibility of such a system they were not considered because short ranges would be used and transmitted power was more than adequate.

3. Design Considerations.

The most important parameter of an imaging system must be the resolution if a useable image is to be formed; that is, a highly detailed picture requires the image forming device to have a high resolution. Rayleigh's criterion for resolution is 1.22 λ/D. This quantity is the bearing resolution, but of primary importance for imaging is the linear separation of two objects to be resolved. The linear separation is given approximately by $r\theta$ where r is the range and θ is the angle in radians. If the resolution of a system were one-half degree, two targets at a range of 1000 meters must be separated by approximately nine meters to be identified as two objects. Nine meters minimum resolution would imply that the target to be imaged at this range would be very large if good detail were expected. So it can be seen that we are dealing with a rather short range device when compared with most radar systems. Furthermore, the transition from the Fresnel (spherical wave) region to the Fraunhofer (plane wave) region is usually taken as $2D^2/\lambda$; therefore, there is a limit to the antenna size to be used at a given wavelength if we are to operate in or near the Fraunhofer region, and focusing may be necessary.

Assuming a one-half degree bearing resolution, D/λ is approximately 140. A one centimeter wavelength would then call for an antenna diameter of 1.4 meters and the transition to the Fraunhofer region would be at a range of about 400 meters. The minimum separation at that range required for resolution then is 3.5 meters. This proposed system would be most useful at ranges of about 100 meters where the minimum separation would be on the order of one meter.

One conclusion can be drawn at this point, and that is a useful system of this type should have a resolution angle smaller than one-half degree. However, this seems like a good value to start with for this first experimental system. The actual design had to start with the availability of microwave power sources. VA-98 reflex klystrons were available with a frequency range of 23.6 to 24.4 gigahertz. Also a 7449A magnetron in the same frequency range could be used. Operating at the mid-frequency of these devices sets the wavelength at 1.25 centimeters. The antenna diameter may now be specified. The Fraunhofer region commences at 372 meters for an antenna five feet in diameter. A plot of near field directivity reduction as a function of range normalized to the quantity $2D^2/\lambda$ [3] indicates that the directivity reduction is less than 0.4 db at 100 meters. The second important specification of antenna size is focal length. As indicated in Section 2, F/D should be greater than 0.5 for good directivity off axis. After a survey of the commercially available antennas, none were listed with these specifications, so an antenna five feet in diameter with a focal length of four feet was ordered custom built.

The theoretical parameters of the antenna at 24 gigahertz are: half-power beamwidth = 0.42°; bearing resolution = 0.57°; linear resolution at 100 meters = 1m; F/D = 0.8; $2D^2/\lambda$ = 372m; directivity reduction at 100 meters = 0.4 db. The half-power beam width calculated above assumes uniform aperture illumination which is not realistic because of the subtended angle of the aperture (68°) compared to the feed pattern.

To produce a symmetrical secondary (overall) pattern the primary (feed) pattern must be symmetrical; therefore, round wave guide was chosen since a symmetrical pattern may be expected using round wave guide operating in the TE_{11} mode. The spacing of the individual elements should be such that the maximum of the pattern of one element will fall on the first minimum of the pattern of an adjacent element. This corresponds to the Rayleigh criterion as discussed before. Referring to Table 15-1 of reference [2], all theoretical maxima and minima may be located. The first minimum occurs at 12mm (0.48 inches); so a spacing of elements on one-half inch centers seems about right.

Since the key feature in this first experiment should be simplicity, a simple crystal video receiver scheme was used. Detection was accomplished by a diode mounted in each feed element. The output of a detector diode was amplified by a broadband microcircuit video amplifier. In addition to being broadband for pulse operation, a high input impedance is required. This is necessary since impedance of the diode detector will vary inversely with the input power. For low signal values the diodes forward impedance will be tens of kilohms. A capacitor charging network was required at the output of the amplifier to hold the output signal until the display device can sample its amplitude. If moving targets are to be observed, either a destructive read out or discharging time constant for the holding circuit appropriate to the frame repetition rate is required to insure that the output is not allowed to persist too long as the scene changes.

The maximum theoretical range is about 470 meters calculated from the equation in Section 2 (which ignores hit-per-scan integration gain). The values assumed in the calculation are: $P_t = 50$ kilowatts; $G_t = 27$ db; $G_r = 48.7$ db; $\lambda = 1.25$ cm; S = 30 microwatts. All the values assumed correspond to actual values in the experimental system. The minimum detectable signal used is a measured value using a 1N26 diode as a detector and, therefore includes system losses. Crystal video detectors are available with a minimum threshold sensitivity of -50 dbm. If this detector were used a maximum range of 3.4 kilometers could be expected. This does not include system losses or integration gain. Atmospheric attenuation was not considered in either calculation since it should be negligible at such short ranges.

4. Experimental

The original planning of this project called for a feed consisting of an array of 81 separate feed elements and detectors arranged in 9 x 9 matrix, to be compatible with the display system. This required 81 individual channels, each with its own detector, amplifier and holding circuit. It became apparent that the cost per channel must be kept low. With this in mind considerable time and effort was expended experimenting with cheap diodes as detectors. The idea was to accept the loss due to a cheap diode and make up for it with increased signal level to keep the cost of this first experiment down. The diode most commonly used in commercially available K band crystal detectors for laboratory work is the 1N26. At the time the price for these diodes was $5.75 in quantities of 100 or more.

Another associated problem had to be considered at the same time. How could the diode be mounted in the feed element? It was kept in mind that whatever method was chosen it must be duplicated 81 times. This very restriction plus cost per channel severely limited the choice of alternatives throughout the entire project.

The first diodes tried were the general purpose types such as 1N69 and 1N127. These diodes were chosen because of their low shunt capacitance. Surprisingly enough these diodes did produce an output when driven by a K band klystron modulated with a 1000 hertz square wave. A HP 415A standing wave detector was used as an indicator. Two possible methods of mounting the diode were apparent. The first was to insert the diode into the open end of the waveguide with one lead grounded to the waveguide wall. The other lead was brought out through a short placed at the end of waveguide. Since the K band

waveguide is so small the size or shape of the pick-up loop could not be varied for optimum response. This form did produce an output 20 db above the noise level.

The second method was to drill through the top and bottom walls of the waveguide and insert the diode through the guide. This aligned the diode with the E field within the waveguide. Once again one lead was grounded to the waveguide and the other diode lead used as the output. The response was improved 9 db over the other mounting method, that is, the output using the E field pick-up was 29 db above the noise level of the HP 415A. For relative comparison the output of a 1N26 using a standard detector mount such as an FXR model K212A is 60 to 65 db above the noise level. When the diode outputs were viewed on an oscilloscope the general purpose diodes are considerably noisier than the 1N26. This was not apparent while using the HP 415A detector due to the 1000 hertz filter in the standing wave detector. The response above the noise level for the last mounting method was about 20 db when using an oscilloscope as an indicator. The VA-98 reflex klystron used was assumed to have an output power of 30 milliwatts (nominal rating). This implies that the minimum detectable signal is 0.3 milliwatts for video detection.

Chronologically the next diode tested was the 1N76. This is an X band video detector and sells for $1.75 in quantities of 100 or more. The coaxial type construction presented a mounting problem for a while, but was finally mounted by drilling a hole in one side of the waveguide the same diameter as the case of the diode. The diode was then inserted in the hole and soldered in place with conducting liquid solder. The solder made a good mechanical

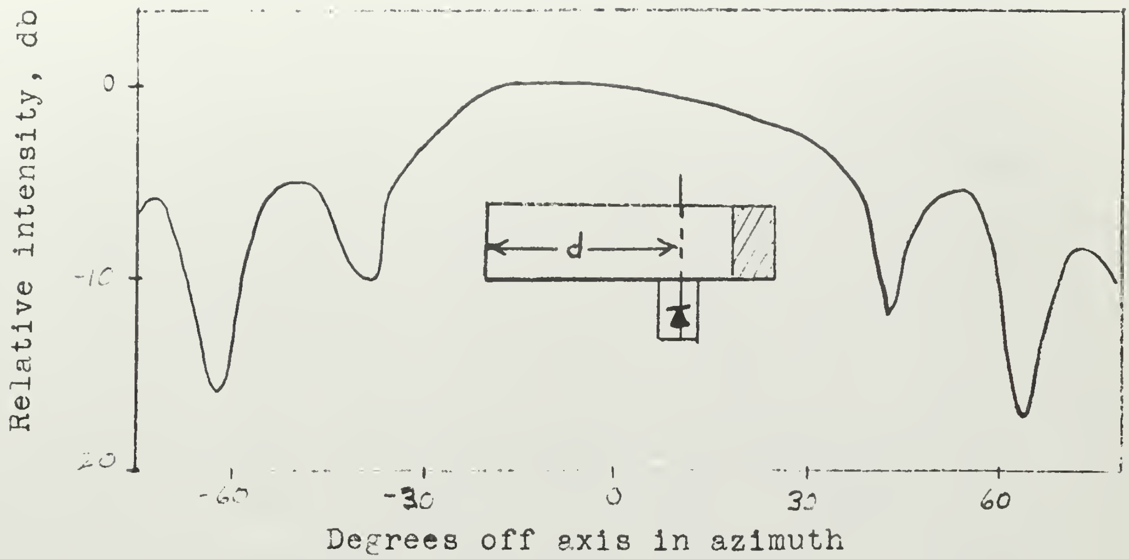
connection and also provided the ground connection from diode case to waveguide. The center conductor of the diode was brought out the other side of the waveguide through a hole only slightly larger than the pin used to connect to the center conductor. Precaution was taken to insure that the diode case did not protrude into the waveguide.

By using an adjustable short in conjunction with this detector the output was only 3 db below the response of a 1N26 in a standard detector. Later work showed that as the signal level is reduced the difference between the responses of the two diodes increases progressively. Although this seemed to be the diode to use, with useable response for a low price, an excessively long delivery time quoted by the supplier prevented its use.

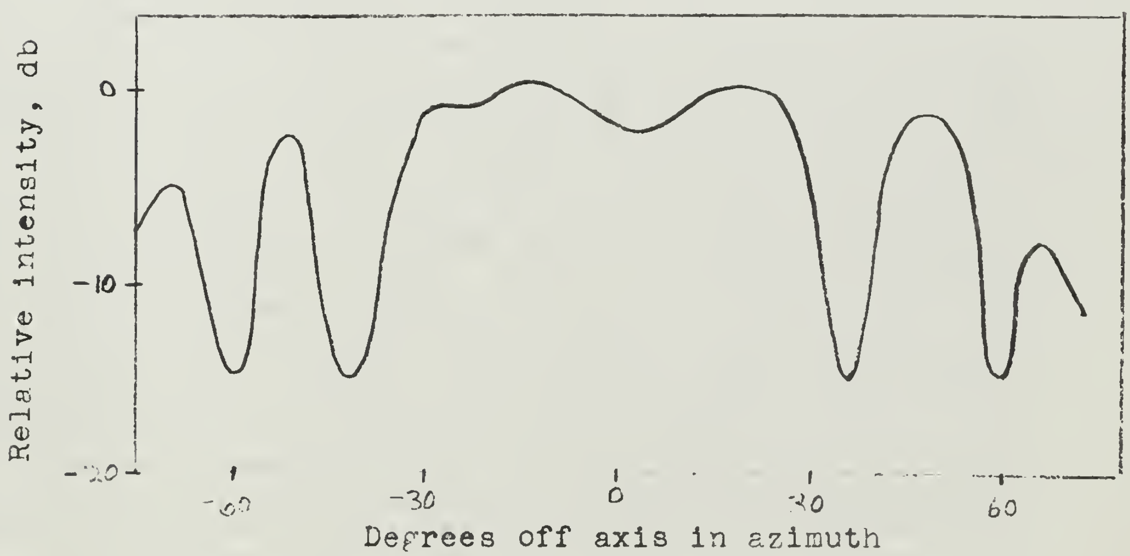
As a last resort a 1N82 was tried because it is used as a mixer for UHF channels in some television sets and, therefore, must handle frequencies close to one gigahertz. The interesting thing about this diode was that it exhibited a pronounced resonance effect depending on its position in the waveguide. The position of the 1N127 and 1N69 tested was not critical so long as the glass bead remained completely within the waveguide. The output level of the 1N82 could be changed 5 db by a very minute change in physical position. This condition was even more acute when the diode was tested in round waveguide. This diode was rejected because of the obviously formidable task of equalizing the responses of an array of 81. The peak response was 14.5 db below the response of a 1N26. At this point in the investigation a decision was made to use the 1N26 as the detector but to build only nine elements arranged in a linear array and simulate a

9 x 9 matrix by physically moving the linear array vertically and construct the result by superposition.

The next problem to be considered was the feed element itself. As mentioned before, circular waveguide was to be used to provide a symmetrical primary pattern. Copper tubing was used with good result. The size decided on was three-eighth inch inside diameter, which corresponds to 0.75λ, and one-half inch outside diameter. A close packed arrangement would be used to satisfy the Rayleigh criterion of resolution. Since the angle subtended by the reflector was only 68° it was necessary to reduce the primary beam width to achieve good efficiency and reduce the first side lobe level. Skolnik [4] notes that greatest efficiency is obtained when the radiation at the edge is 8 to 12 db below that at the center. It was found that the position of the detector diode with respect to the receiving end of the tubing made a significant change in the pattern. A sketch of a feed element is shown in Figure 2(a). Several patterns were run in the anechoic chamber at various diode positions. The pattern became successively narrower as the spacing was increased. For a spacing of 2λ the 10 db beam width was 132° and 3λ reduced this to 81°. However, when the spacing was increased to 3.5λ the beam width decreased to 72° but the center of the pattern dipped approximately 2.5 db. Patterns for 3λ and 3.5λ are shown in Figure 2. Because the pattern for 3λ spacing is fairly flat topped the radiation intensity at the edge of the reflector will be only 4.5 db down from the center; but since the pattern decreases rather rapidly the efficiency could be better than the 4.5 db figure would indicate.



(a)



(b)

Figure 2. Primary radiation patterns for diode location, d, within the feed (a) d=3 (b) d= 3.5 .

A provision for tuning or peaking the response of each feed element was planned. By using a short piece of three-eighth inch diameter aluminum stock as a sliding short it was found that the response could be peaked about 3 db in the first attempt to build a feed element. However, in the final design the feed element was made 5 λ long with the diode placed 3 λ from the front. With these dimensions the variation in response as a function of sliding short position was less than one db for the entire travel of the short. The end of the tubing was closed with a small piece of absorbing material and no further tuning was attempted. The response with this arrangement was equivalent to the peak response of the original detector. The original detector using the sliding short was 2 3/4 λ with the diode placed 3/4 λ from the end. Incidentally, the 10 db beam width using this feed was 144°.

No attempt was made to analyze the field patterns within the tubing or to determine the standing wave ratio of this detector mount. After work with the round waveguide started all work was conducted in the anechoic chamber since adapters, fittings, slotted lines, etc. were not available for round waveguide. Further data were taken when it was found that the vertical and horizontal diffraction patterns using a point source were not identical. This seemed to indicate that the primary pattern of the feed was not symmetrical. The patterns shown previously were in the horizontal plane or an azimuth pattern. The test stand in the anechoic chamber did not have a provision to take a vertical pattern. The test feed was rotated 90° so that the E field pick-up was horizontal. A waveguide twist was used to change the polarization of the source to horizontal, and the test stand was rotated in the normal horizontal plane to plot

the pattern. This should be equivalent to an elevation pattern. The resulting pattern is shown in Figure 3 for comparison. It is readily seen that the elevation pattern is considerably broader than the azimuth pattern.

It was assumed that the predominant mode in the feed element was TE_{11}. Calculations of cut-off wave lengths indicate that higher order modes will not propagate in this size guide for $\lambda = 1.25$ centimeter; however, since the detector is only 3λ down the guide these calculations should not apply precisely. A plot of detector response verses detector polarization using a vertically polarized source is shown in Figure 4. It should be noted that the response does not go to zero at 90° (cross polarization) but is about 10 db above the noise level of the HP 415A standing wave detector used as an indicator. This indicates that there are definitely other modes present within the waveguide.

The next test to be performed was that of obtaining the basic diffraction pattern of a point source. This was accomplished by traversing a single feed element and detector across the front of the aperture in the focal plane. Vertical and horizontal patterns were taken to determine the degree of symmetry of the pattern. The results obtained indicated the beam width, the side lobe level and an indication of expected resolution available. Also, a qualitative measure of the phase error across the aperture due to manufacturing tolerances could be made.

In order to use a clear range to avoid spurious reflections from obstructions, the receiving antenna was erected on the sixth floor roof of one building and the point source on the roof (third story)

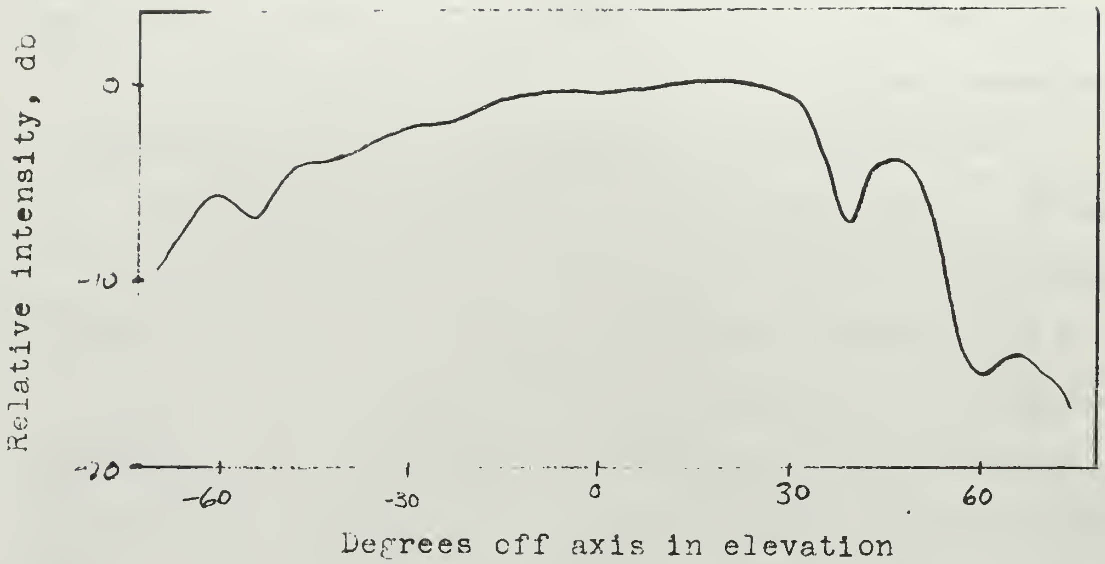


Figure 3. Primary radiation pattern for horizontal polarization.

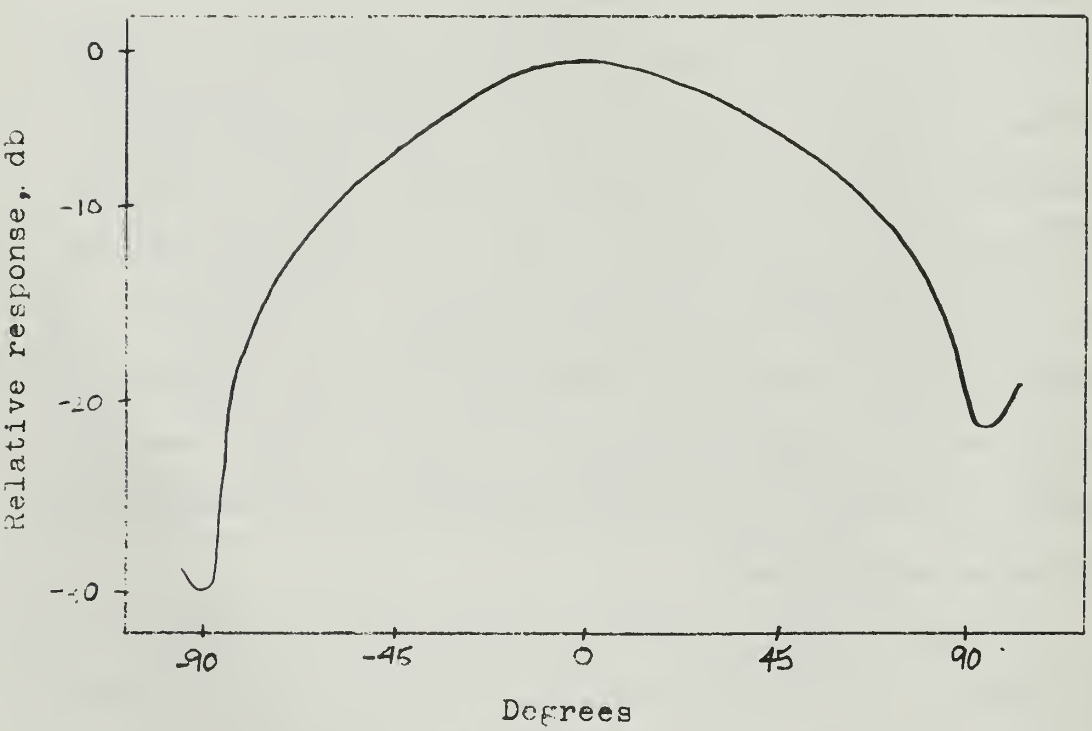


Figure 4. Relative detector response as a function of polarization orientation.

of an adjacent building. The point source was simulated by a klystron driving a 12.5 centimeter diameter paraboloid antenna. This point source was placed near a convenient power outlet at an estimated distance of 100 meters. The distance was later determined more accurately using a surveyor's transit and triangulation to be 114 meters. The ray paths from the source may be considered parallel at this distance. The experimental set up is illustrated in Figure 5.

Several patterns were run before they began to take the expected shape. The alignment of the source and receiving antenna was a small problem at first but the greatest source of error was the reflector itself. Reasonable care had been exercised when the reflector support was built not to distort the reflector, but nevertheless distortion occured. This was corrected rather simply by loosening all the mounting screws directly attached to the reflector and then re-tightening only finger tight. This held the reflector firmly in place, or firmly enough for our purposes, and did not cause any distortion. Horizontal and vertical diffraction patterns are shown in Figures 6 and 7. The klystron source was modulated with 1000 hertz square wave and a HP 415A was used as an indicator.

If uniform illumination of the aperture is assumed the first minimum should occur at $1.22\ \lambda/D = 0.57^{\circ}$ and 3 db beam width of 0.42° would be expected. The vertical pattern has a 3 db beam width of 0.7° and the first minimum occurs at 0.82°. Also, with uniform illumination, the side lobe level should be -17.6 db [1]. The actual side lobe level is -14.5 db for the vertical pattern. As noted earlier the horizontal pattern is considerably broader and its shape makes it difficult to make meaningful comparisons

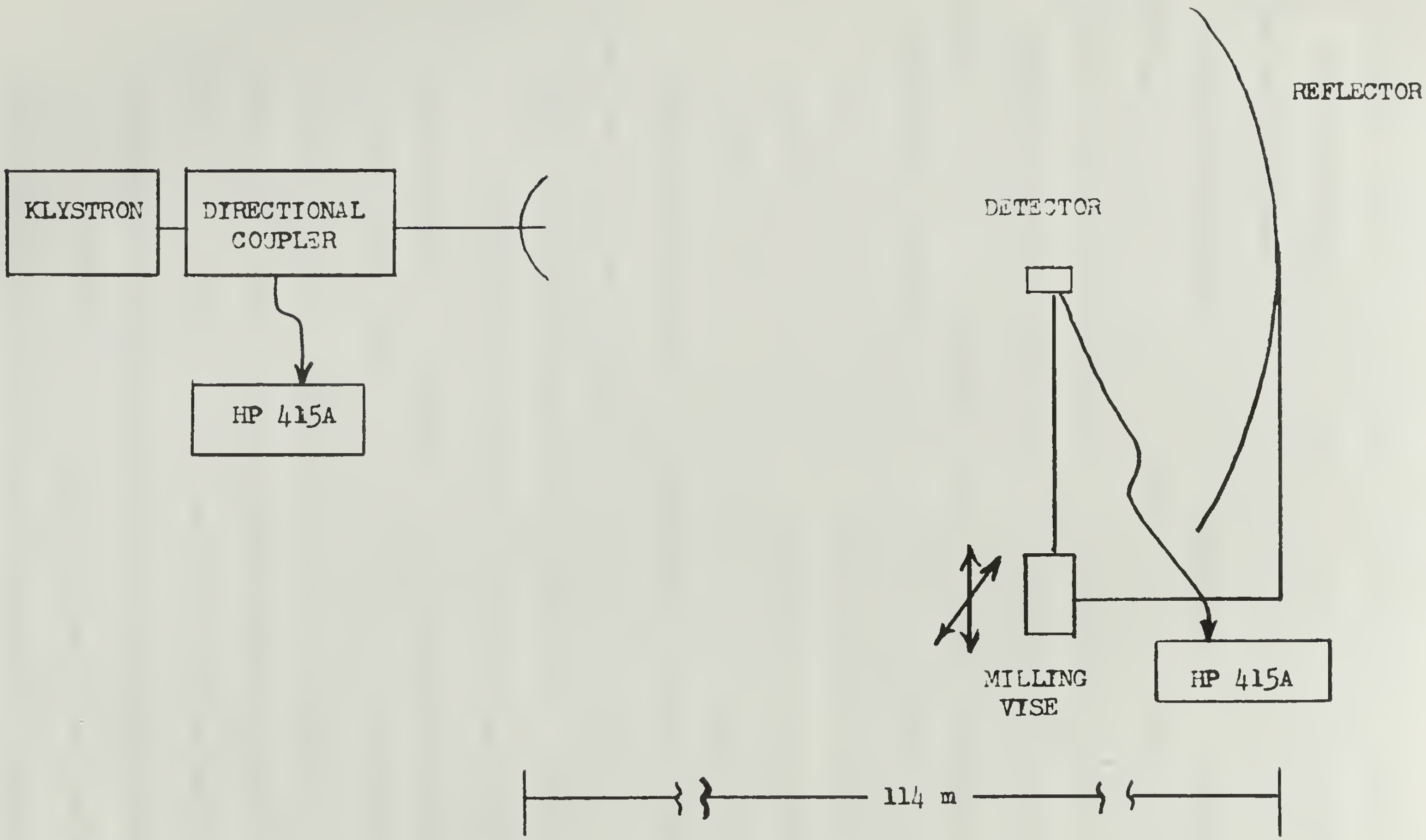


Figure 5. Experimential set up.

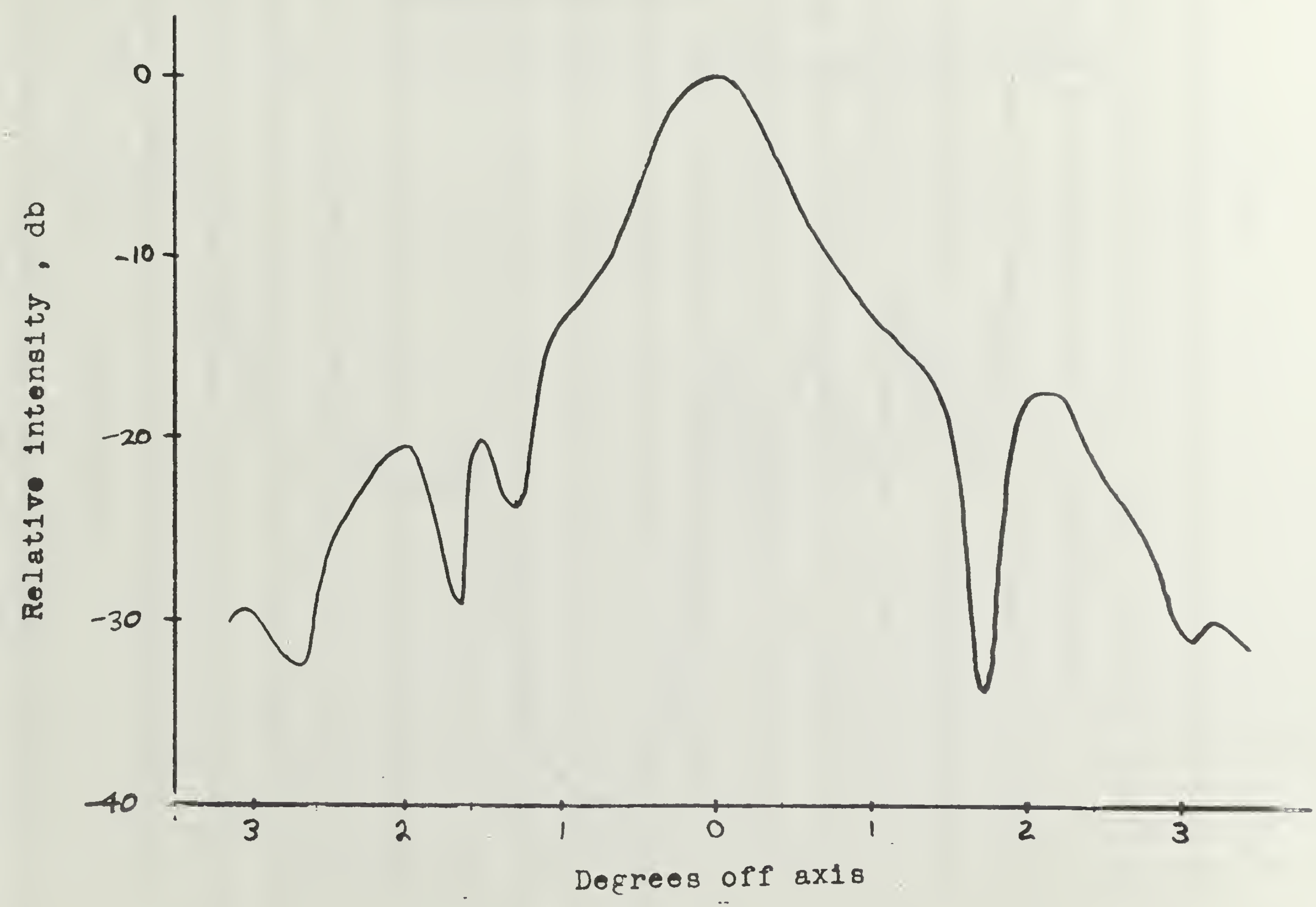


Figure 6. Single source horizontal diffraction pattern.

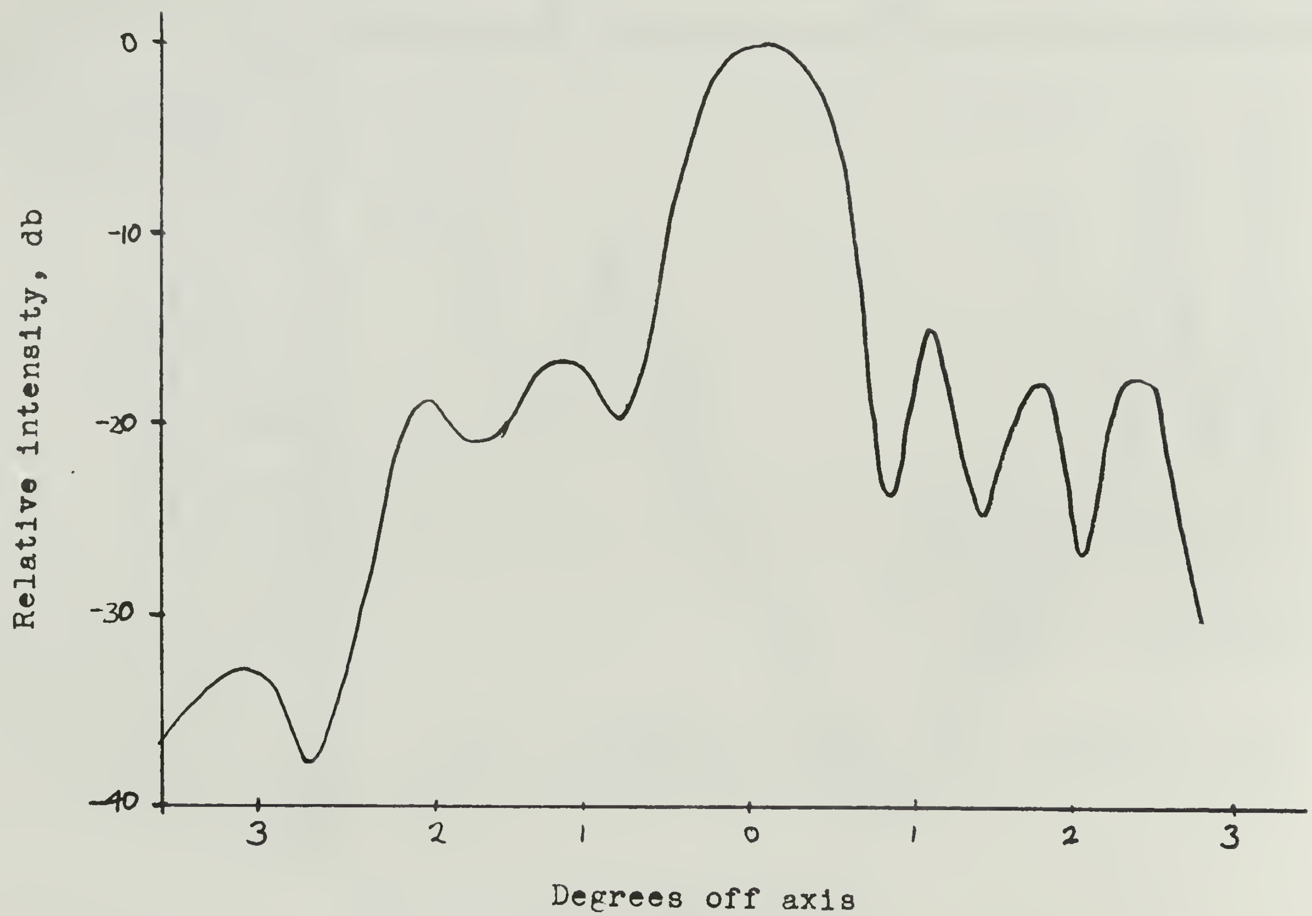


Figure 7. Single source vertical diffraction pattern.

between the patterns or between this pattern and theory. A close inspection of the horizontal pattern compared with the vertical indicates that the major difference is that the first minimum on either side of the major lobe has been filled in and the first side lobes are joined with the major lobe. This is probably due to the differences in the primary patterns discussed before.

There seems to be a wide discrepancy between the data from the vertical pattern and theory; however, it must be recalled that the aperture illumination by the feed is not uniform but tapered to 4.5 db at the edge of the aperture. Tapering the illumination has the effect of broadening the main lobe, which could account for the greater beam width and wider separation of the first minima, but it also lowers the theoretical side lobe level and the actual side lobe level increased. The most important factor affecting the directivity and side lobe level in this case is the distance from the point source to the aperture. The receiving antenna is in the far field of the small antenna simulating a point source; however, the point source is well within the near or Fresnel region of the receiving antenna. The main effects on a beam pattern in the Fresnel region is a broadening of the major lobe and an increased side lobe level. These two facts, tapered illumination and near field effects, qualitatively explain the apparent discrepancies in the observed data.

The ability to separate two objects was determined by using two active point sources. The two sources were placed at the same range as before (114 meters) and horizontal diffraction patterns taken for various separations of the sources. The Rayleigh criterion for resolution shows that a separation of 44 inches should be detectable.

The result of this test is shown in Figure 8. By adjusting the two sources to nearly the same level and by careful data taking using the HP 415A again it was possible to resolve the two sources with a separation of 44 inches. The depression between the sources in the pattern is less than 1 db and would not be noticeable on an intensity modulated display. The feed element movement across the aperture is only four-tenths inches from one peak to the other. To resolve the two objects with individual fixed feed elements at least three would be required. One at each maximum and one at the relative minimum between them. This implies an element spacing on two-tenth inch centers if the different signal levels were to be distinguished.

The two sources were arbitrarily separated 83 inches and a new diffraction pattern obtained. The minimum between the two maxima was down 4 db and the required spacing of fixed feeds to display would be four-tenth inch center to center. The 4 db difference in signals should certainly be observable even if there were some averaging of signal levels between the feed elements. This linear separation corresponds to 1.06°. The choice of tubing size for the elements had limited the element spacing to a minimum of one-half inch center to center. Furthermore, the feed elements had already been constructed and the design changed so that the minimum spacing was about five-eighth inch. The design change consisted of not soldering the diode in place but instead holding the diode with a coil of stiff wire soldered to the tubing. The coil was made with a slightly smaller diameter than the case of the diode so that the diode had to be screwed into place in the coil and tubing. To improve the rigidity the end of the wire that formed the coil was wrapped around the tubing and soldered. The liquid solder connection had proved very fragile.

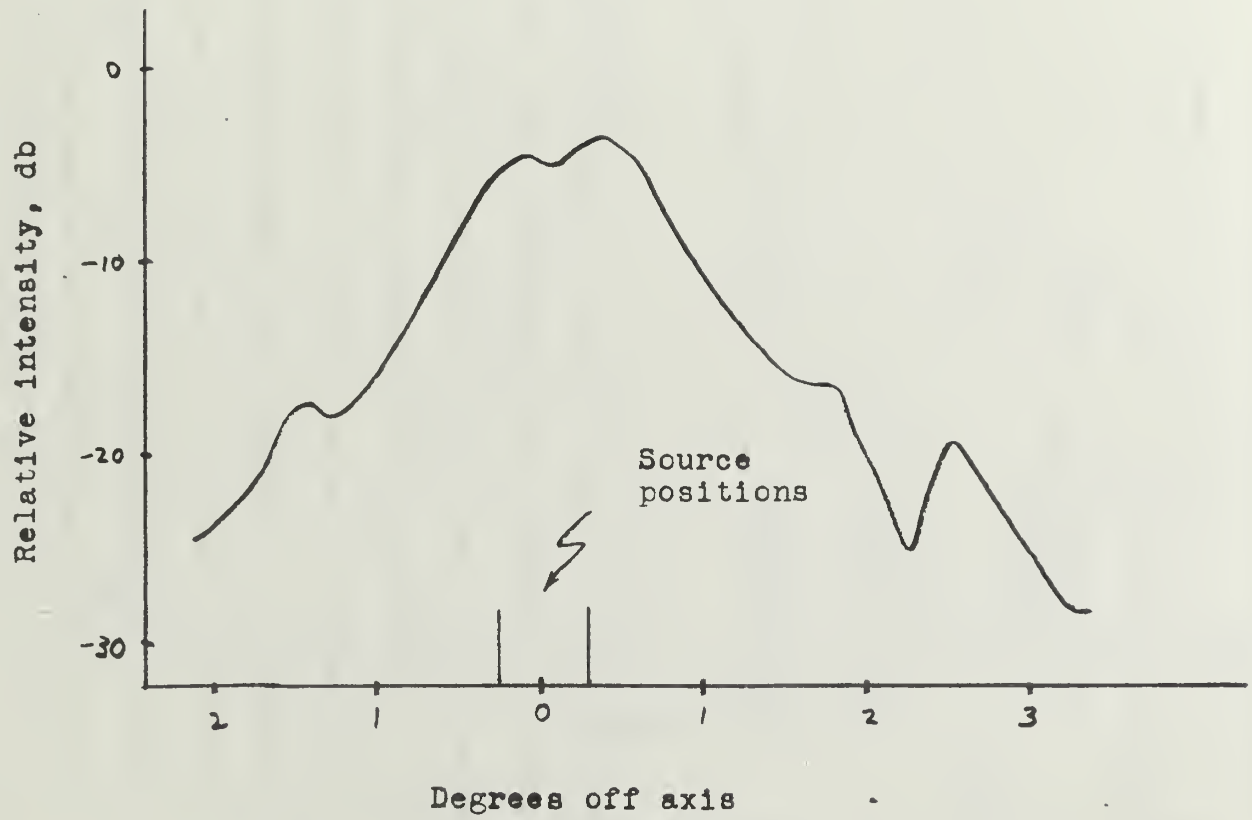


Figure 8. Two source horizontal diffraction pattern.

The spacing between the two sources was increased to 102 inches. This spacing was chosen by extrapolation from the previous two patterns. The spacing of elements to resolve the two objects was five-eighth inch and the minimum between the two maxima was down 20 db as shown in Figure 9. This separation corresponds to 1.3°.

For one-way transmission the received power at the receiver, P_r, is given by Silver [1] as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 r^2}$$

where

$$G_t = \frac{4\pi \rho_t A_t}{\lambda^2}$$

$$G_r = \frac{4\pi \rho_r A_r}{\lambda^2}$$

Assuming that the antenna aperture efficiency is 50 percent for both antennas, a calculation may be made of the power lost in transmission. The gain of the small antenna simulating the point source was computed to be 27 db and that of the receiving antenna was 48.7 db. The received power at a range of 114 meters is 25.5 db below the transmitted power. The equation above; however, assumes that the transmitting antenna is in the far field. The loss of directivity or gain was shown earlier to be 0.4 db at this range, so, to determine the actual gain or more properly the antenna aperture efficiency this correction should be made. Therefore the calculated transmission loss is 25.9 db.

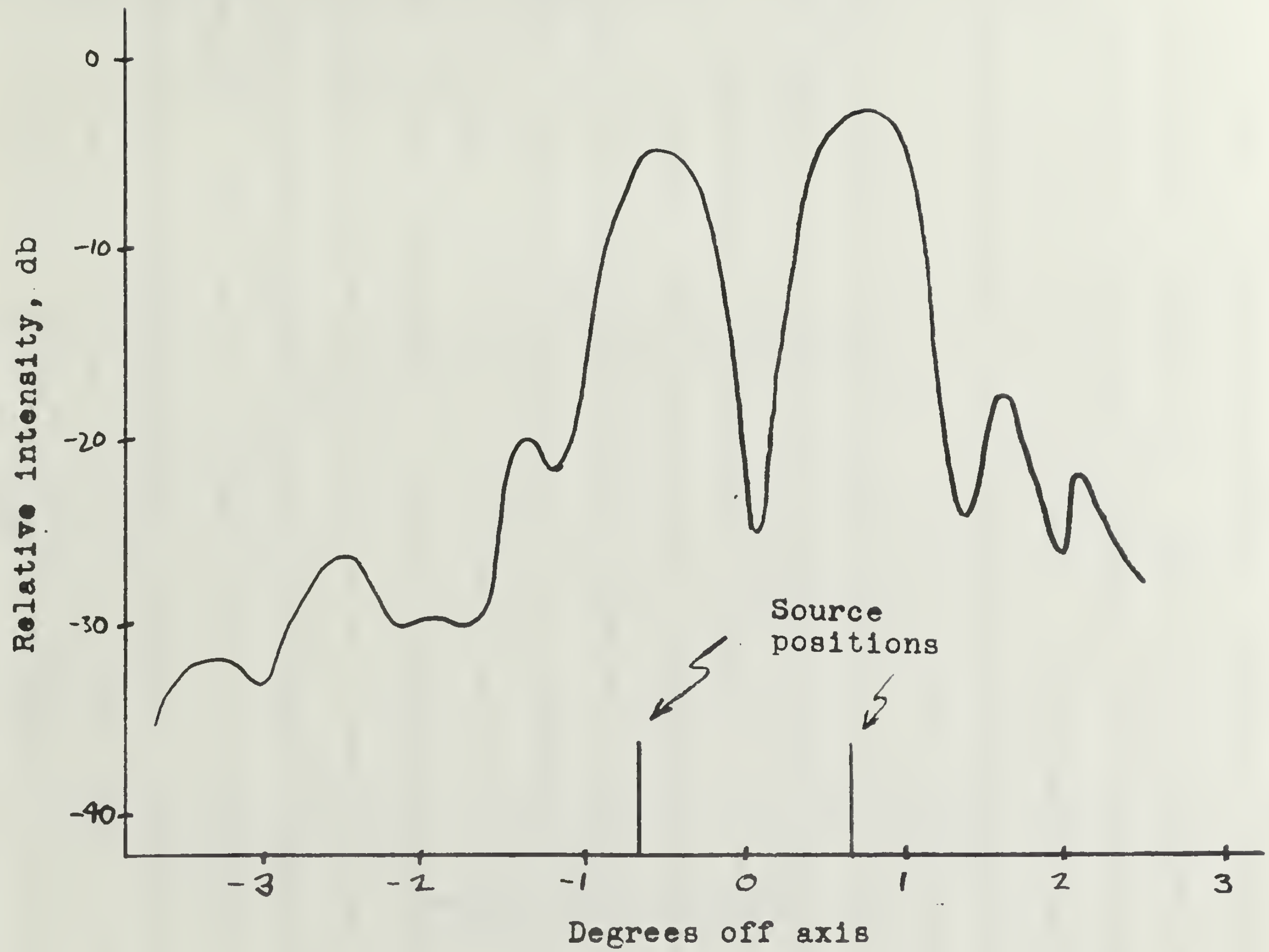


Figure 9. Two source horizontal diffraction pattern.

The actual transmission loss was determined by measuring the relative power received with a HP 415A standing wave detector and then measuring the transmitted power, using a directional coupler, with the same meter and identical gain settings. After correcting for the known attenuation of the directional coupler, the transmitted power loss was found to be 24 db. This indicates that aperture efficiency of one or both, antennas is greater than the 50 percent which was assumed earlier. Since the gain of the small test antenna is not known it would be fruitless to try to calculate the actual receiving antenna efficiency.

Figure 10 illustrates the diffraction pattern obtained by moving a single feed element through the focal plane along the antenna axis.

Diffraction patterns were taken for a single point source displaced from the antenna axis in elevation and are shown in Figures 11 and 12. Two degrees off-axis corresponds to 2.85 beam widths and four degrees is 5.7 beam widths from the center. As shown the pattern's major lobe is broader but the side lobe level is unchanged, when compared to on-axis, for a displacement of 2°. However, when displaced 4° the pattern has begun to degrade significantly. The main lobe is slightly wider than the previous pattern but the first side lobe is now -11 db compared to the main lobe. This pattern is probably still satisfactory for imaging depending on the dynamic range of a display device; therefore, it would be expected to be able to image a scene subtending an angle of 8° from the antenna with possibly some slight degradation at the edges.

It was noted that the elevation pattern for 2° off-axis was very similar to the on-axis pattern in azimuth. After carefully checking the alignment of the receiving antenna and point source in azimuth,

Figure 10. Axial focusing response.

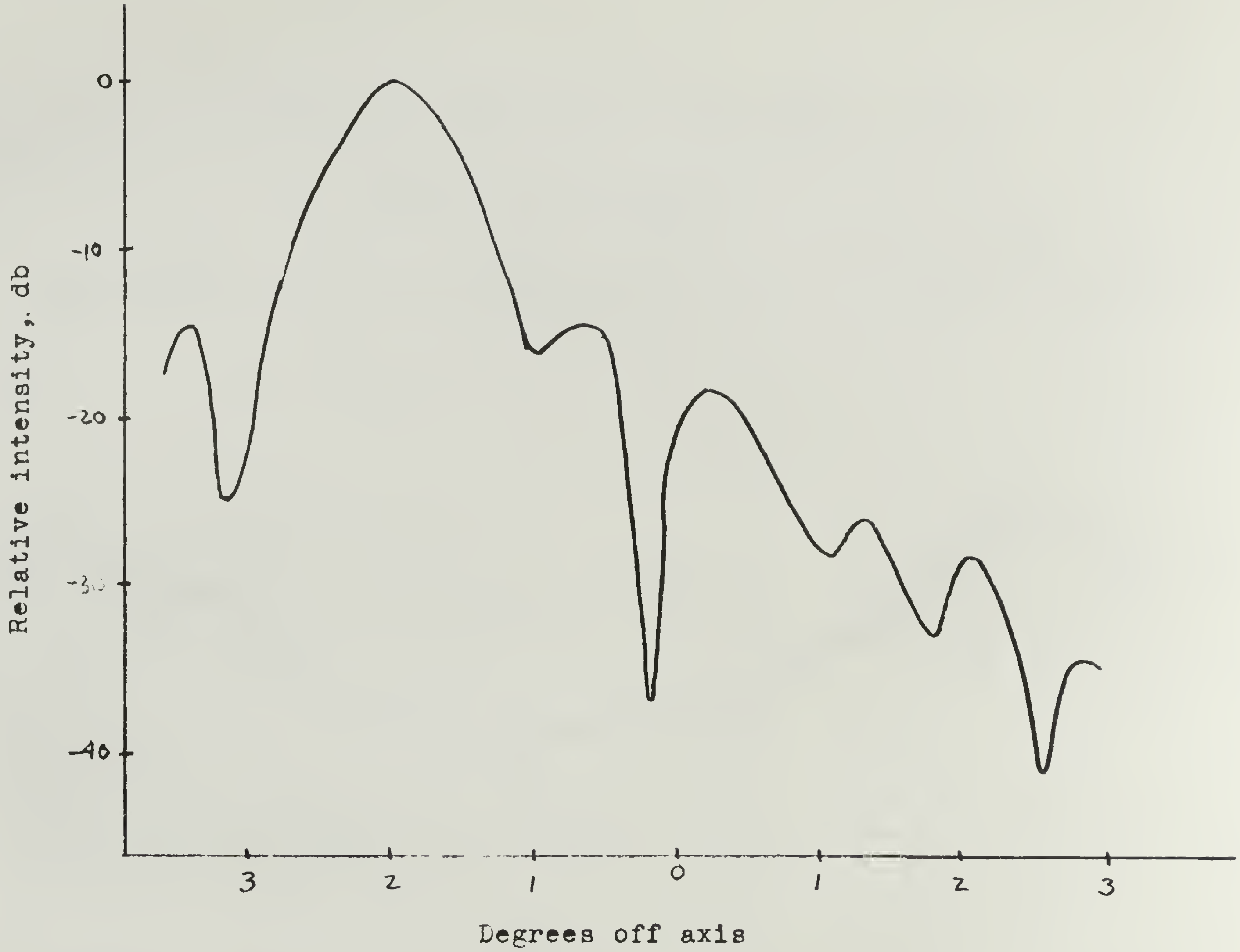


Figure 11. Single source 2^{0} off axis.

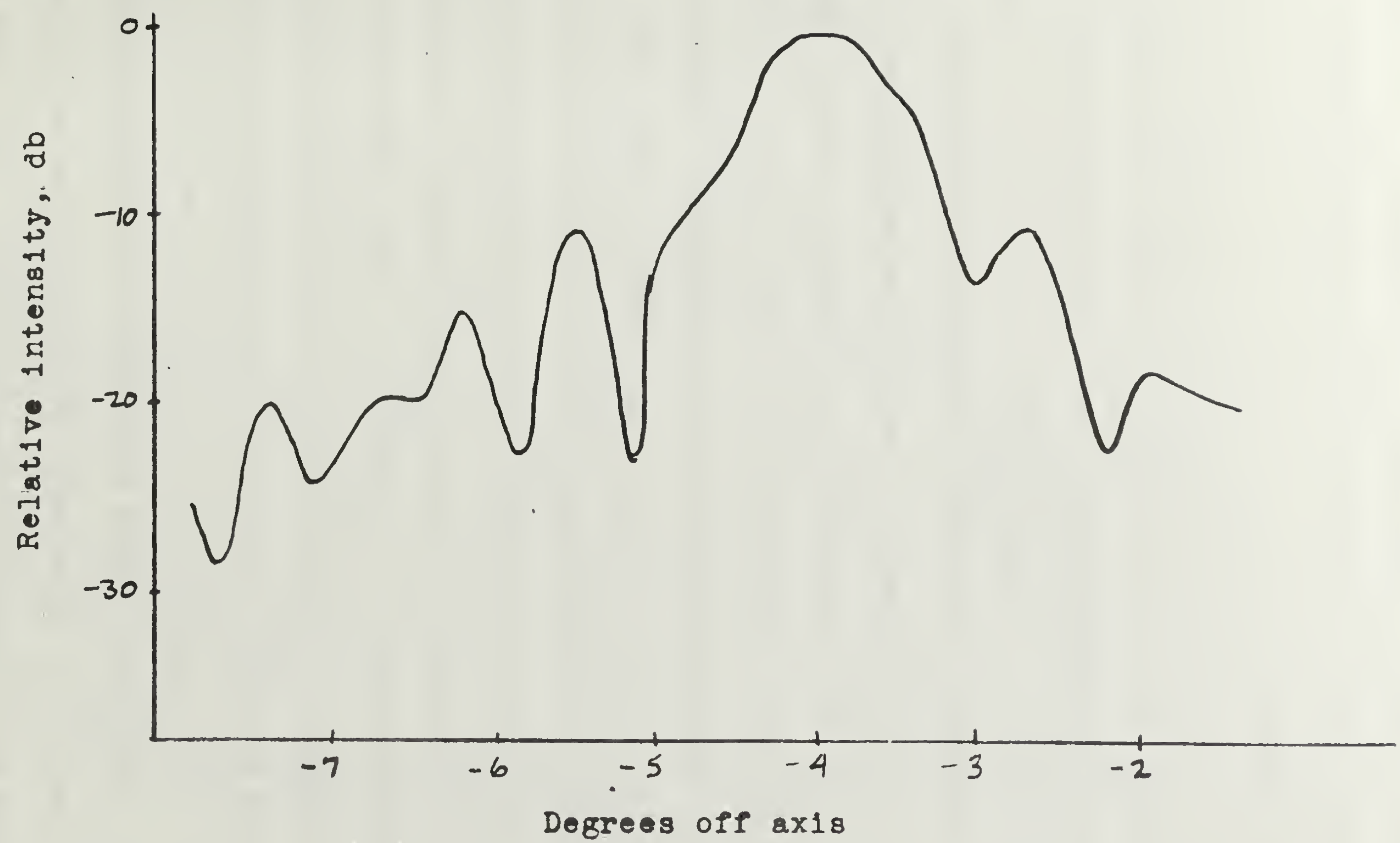


Figure 12. Single source 4^0 off axis.

it was concluded that this was a coincidence. This seems to be borne out in later work when a linear array was constructed. It will be seen that the vertical and horizontal patterns are very similar and the alignment must not have been a factor in the discrepancy noted in earlier patterns.

The next step was to build and test a linear array using nine feed elements spaced on five-eighth inch centers. This spacing is the minimum possible due to the feed element-detector design as discussed before. A radiation pattern of the array was run using the center element to determine if the presence of the other feed elements affected the pattern. The response was essentially the same over the angle subtended by the reflector. The next step was to run diffraction patterns using the center element as the only detector to determine what effect the array had on the patterns as compared to those when only a single element was used. After each pattern had been completed the array was positioned so that the center element was at the peak of the major lobe in azimuth and elevation. The output of each element was measured and plotted on the diffraction pattern. The plots for a single point source are shown in Figures 13 and 14. The solid line represents the diffraction pattern and the circles the output of each individual feed element plotted at their angular positions relative to the diffraction pattern. The element outputs agree well enough that the general shape of the pattern is evident. The discrepancies between element outputs and the diffraction pattern are probably due to some averaging of signal levels "viewed" by each element and also due to mutual coupling between elements.

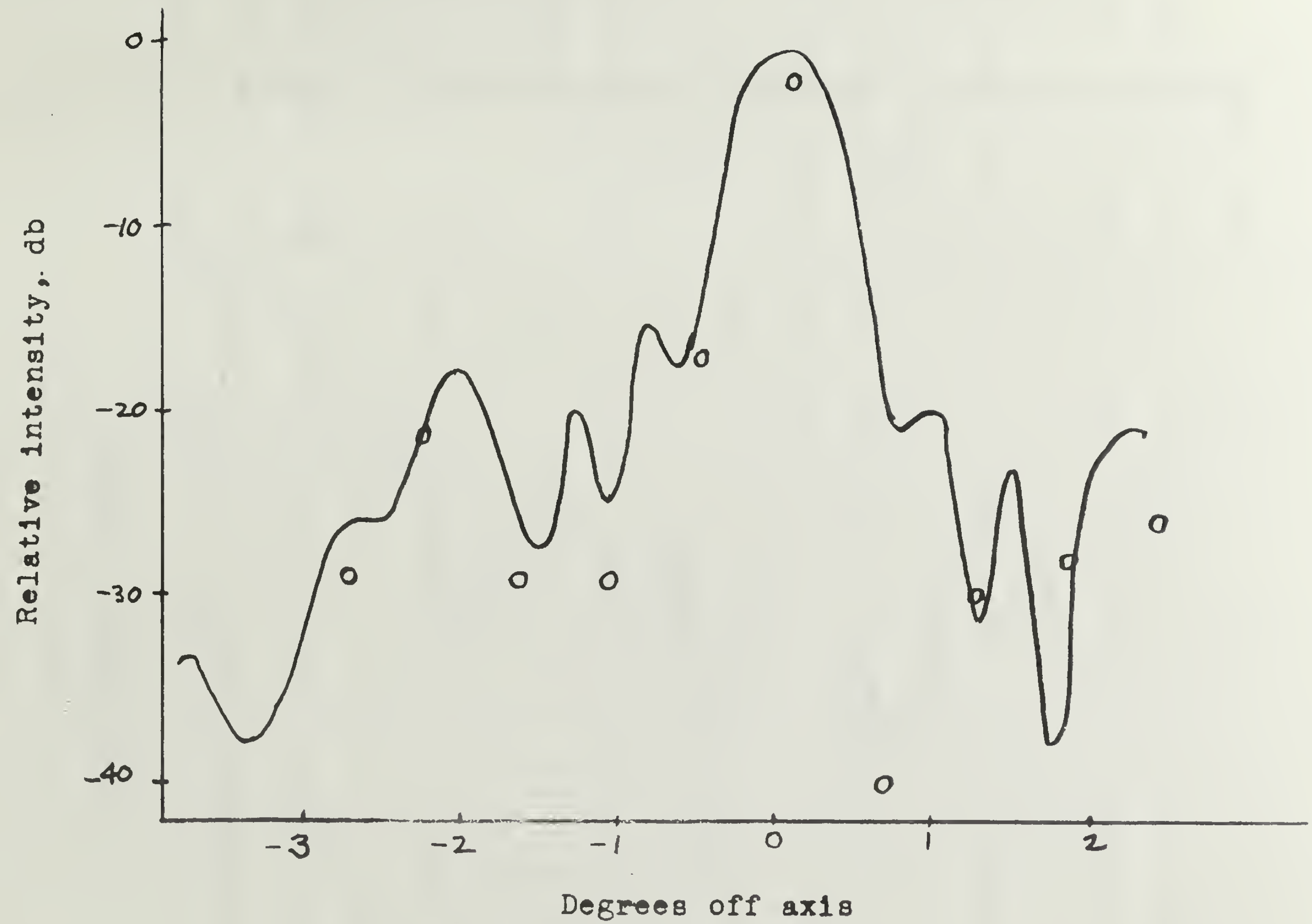


Figure 13. Single source vertical diffraction pattern.

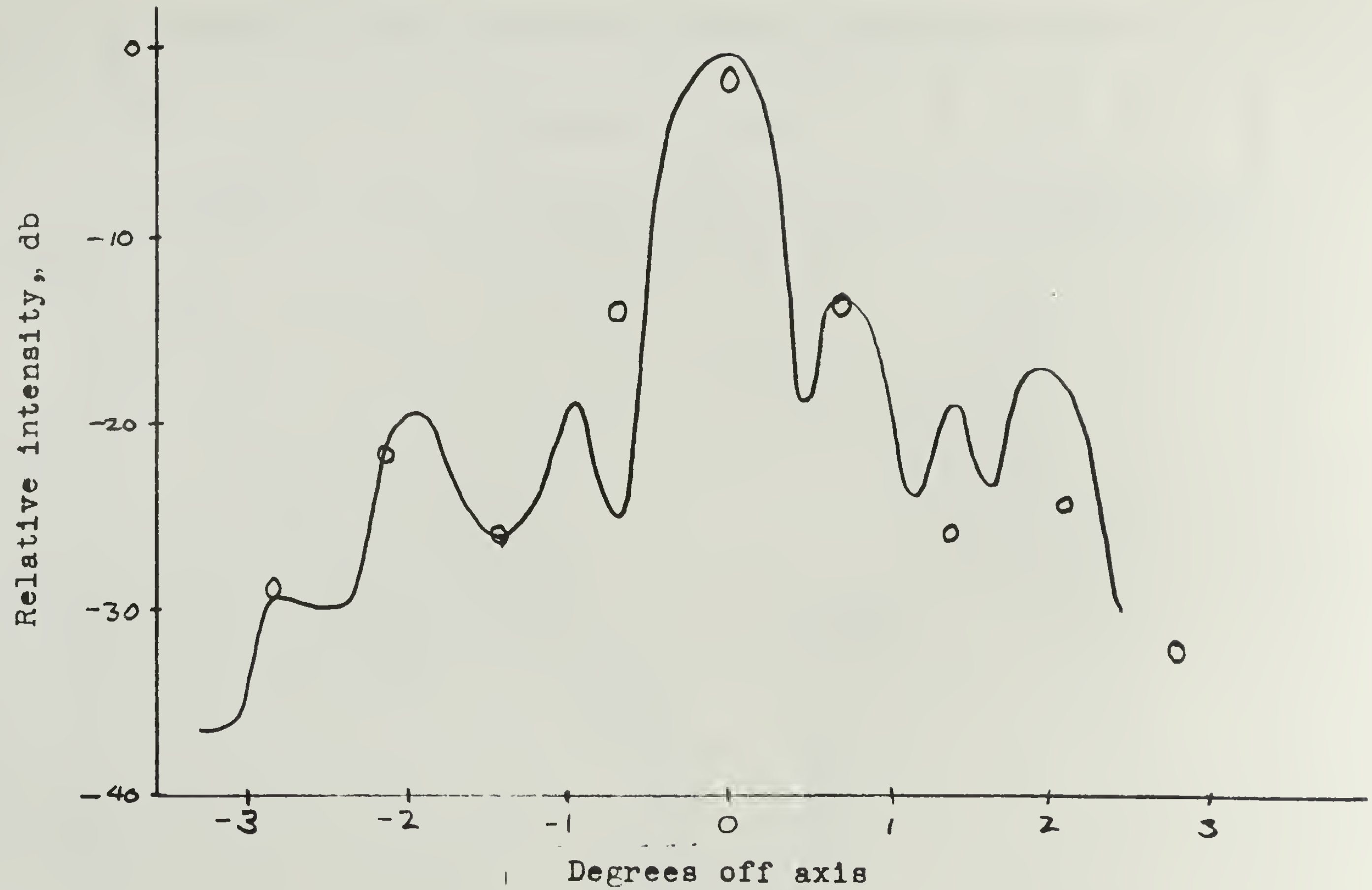


Figure 14. Single source horizontal diffraction pattern.

Figure 15 displays the same information for two point sources operating simultaneously with 102 inches separation at 114 meters. The only difference in procedure was that the center element was aligned on the center minimum.

Field mapping of the diffraction pattern of both one and two point sources was accomplished by manually recording the outputs of each of the nine linear elements for nine vertical positions across the field. The vertical spacing was the same as horizontal to simulate a square array of 81 elements. The "pictures"produced are shown graphically in Figure 16. In both cases the point sources are clearly discernible. Photographs of the linear array and imaging system are shown in Figures 17 and 18.

Further testing was to include field mapping of point sources simulated by corner reflectors and, ultimately, shaped targets by illuminating them with a magnetron transmitter located at the receiver site. The antenna to be used with the transmitter was the same type used to simulate point sources for one-way transmission. It provided a 3 db beam width of 7° which would have illuminated almost the whole area that the receiver was capable of viewing. The nine element array only covers a subtended angle slightly less than 6° so the illuminator coverage would have been adequate. The magnetron was not available for use and this part of the project had to be dropped.

The area masked by the feed support and the linear feed aray itself is 0.29 square feet as compared with the aperture area of 20.3 square feet. Referring to a plot of aperture blockage effect on side lobe level and directivity in reference [3] , the pattern degradation is negligible. If the whole array of 81 elements were used the blocking

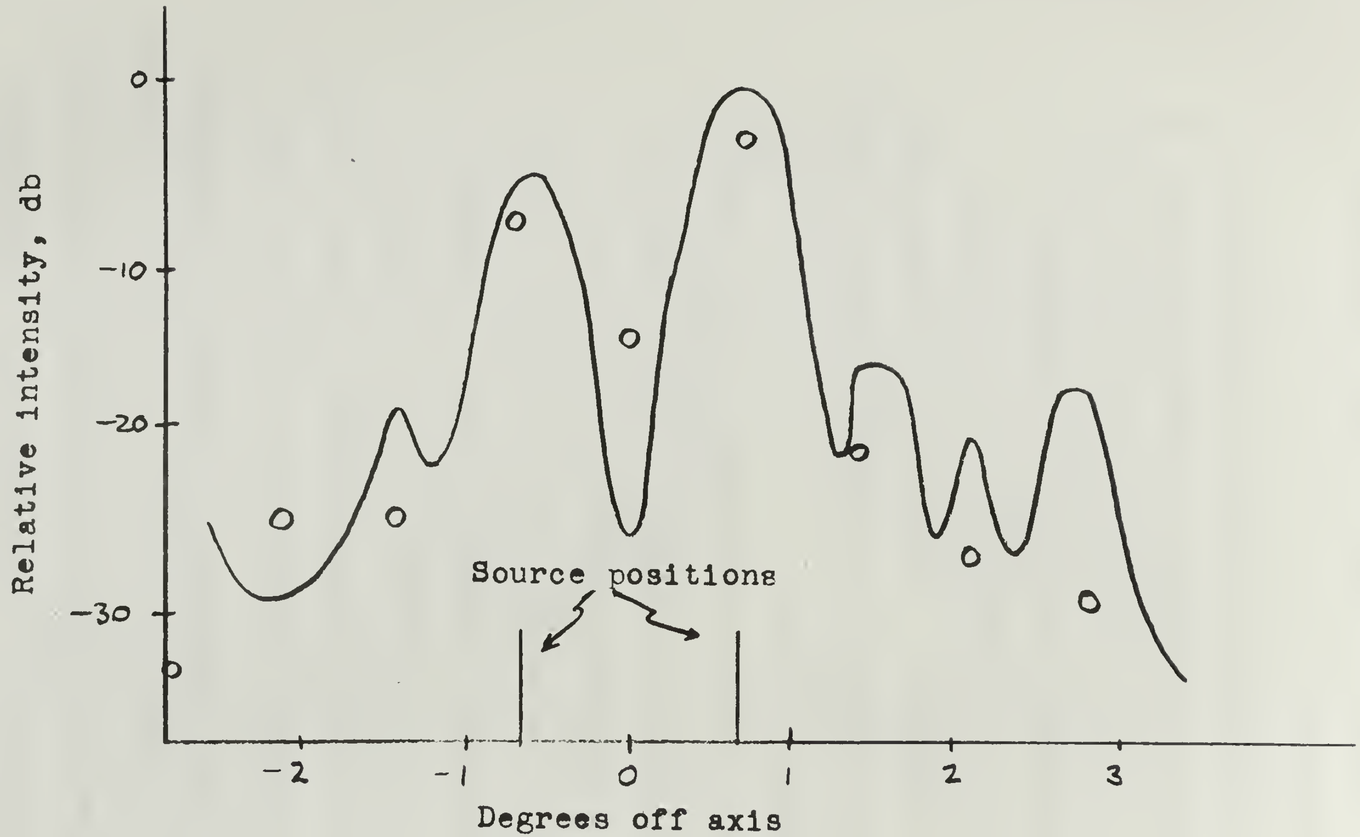


Figure 15. Two source horizontal diffraction-pattern.

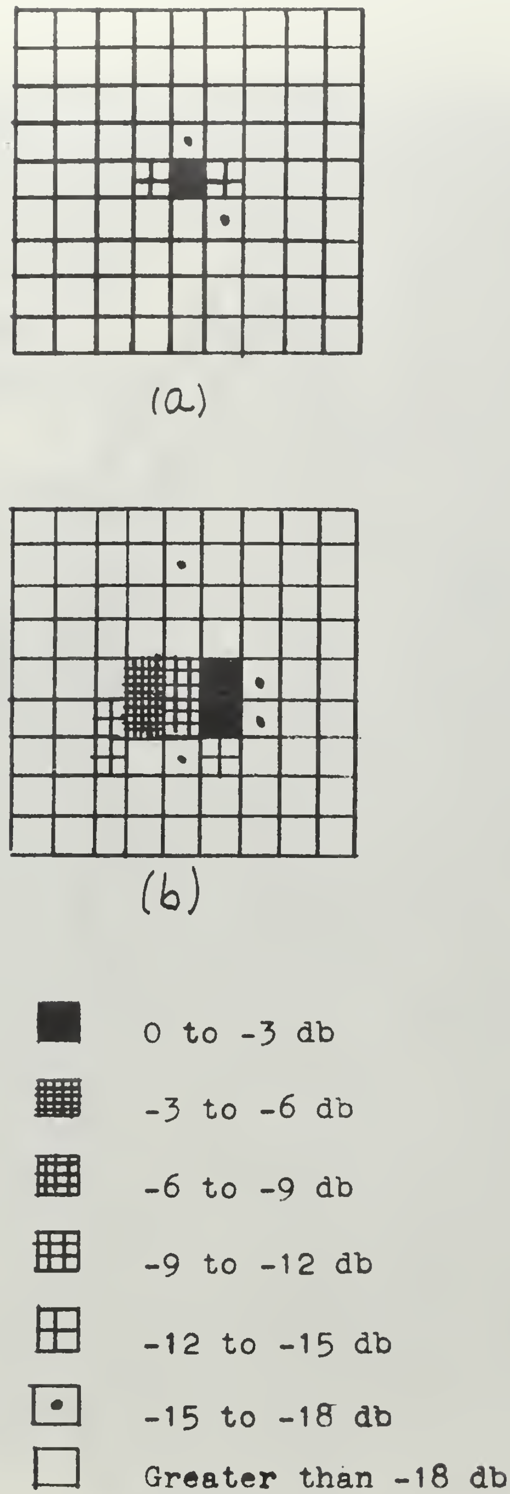


Figure 16. Intensity response of image array (a) one source (b) two sources.

Figure 17. The linear array.

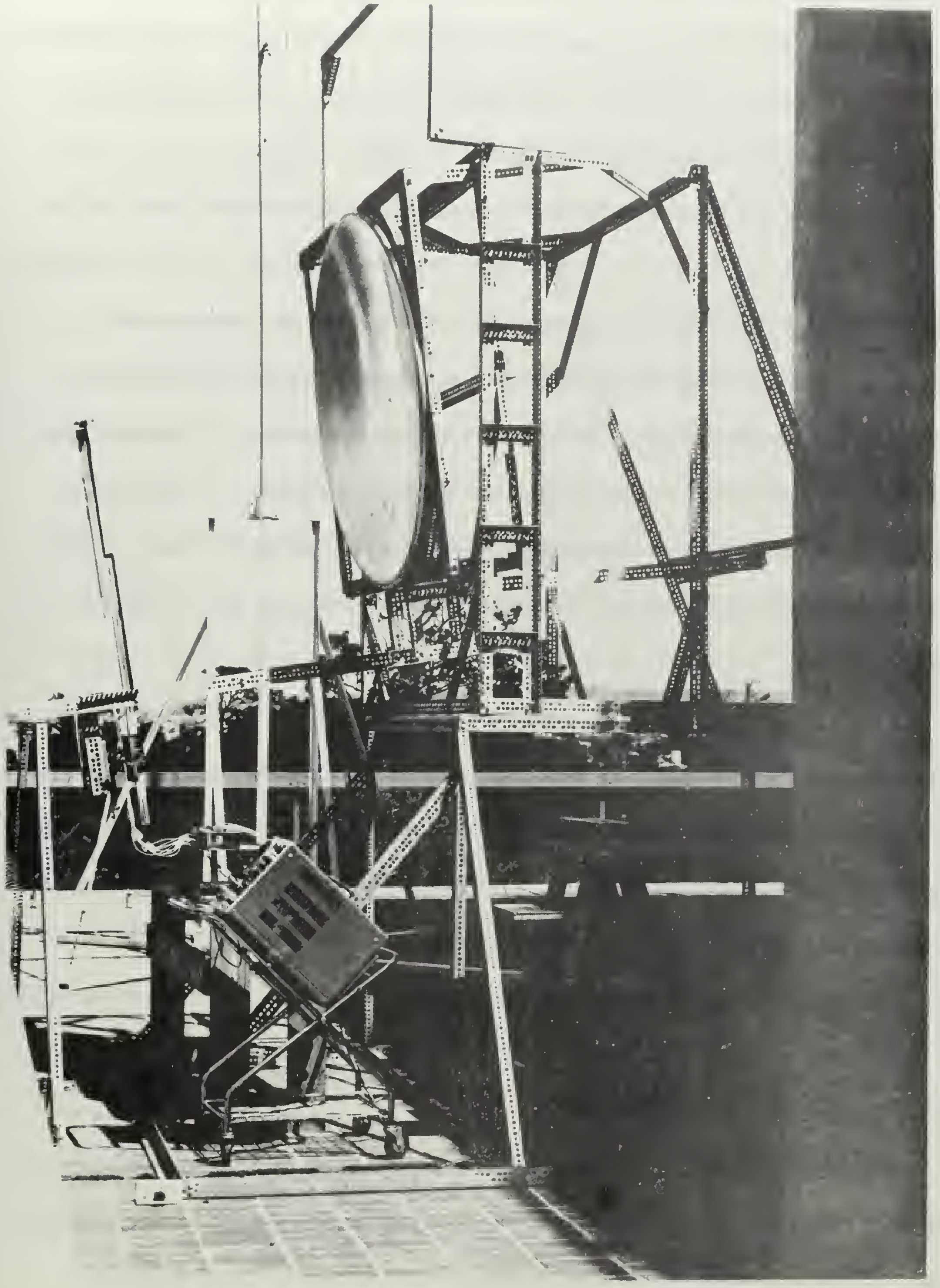


Figure 18. The imaging system.

would only be one-half square foot and still negligible effects would be expected. The plot does not strictly apply to this case but probably may be used as a rough estimate of blockage effects.

All data to this point had been collected using a HP 415A standing wave detector as an indicator. The next step was the amplifier and rectifier-holding circuit design and testing.

The amplifier was required to handle one microsecond pulses at a pulse repetition frequency of 500 pulses per second. This required that the amplifier band width should be at least one megahertz with as much gain as possible to produce a maximum output of one volt. Also the pulsed operation placed severe requirements on the rectifier-holding circuit. The output capacitor should charge in one microsecond and be capable of holding the charge two milliseconds; therefore, a low amplifier output impedance was necessary for a fast charge time.

Several amplifiers were considered, keeping in mind that they should be small, simply constructed and low cost. Integrated circuits seemed to best satisfy all requirements. The Fairchild μ702C linear integrated amplifier was chosen. The amplifier specifications are listed in the Appendix A. Complete operating characteristics, applications, and circuit description are contained in reference [5,6]. The schematic diagram of the complete amplifier, rectifier-holding circuit is shown in Figure 19.

A feedback configuration was chosen to make the gain variable so that all channels could be adjusted to give equal outputs for a given input. When the amplifiers were constructed using five percent resistors the mean gain was 123.

The circuit consists of a simple feedback amplifier with a nominal gain of 123. The dc level of the output is removed by the RC circuit at the amplifier output. The diode provides a low RC time constant for charging and a long RC time constant on discharge. The dc output voltage as a function of relative input power to the detector is shown in Figure 20 for both one kilohertz square wave modulation and one microsecond pulses at 500 pulses per second.

When tested it was found that only four detectors and amplifiers could be used simultaneously to provide a useable dc output. This was because of the wide variation of individual detector responses (up to 9 db). This was easily corrected for when the HP 415A was used as an indicator, but it was not possible with the amplifiers because of the non-linear dc output. A solution to this problem is to make the feedback resistor variable with a range from 1 kilohm to 100 kilohms.

The single and double source tests previously run using the HP 415A were then repeated, using the microcircuit amplifier with four center elements to simulate a 4 x 4 array. The results of the 4 x 4 matrix is shown in Figure 21 for both single source and double source. Voltage values are shown for each element. By using Figure 20 a comparison of Figures 16 and 21 may be made. The only apparent discrepancy is that in Figure 16 the response from the two sources appear in adjacent rows but not in Figure 21. The explanation is that when the data was taken for Figure 21 the feed and reflector were carefully aligned to give the maximum output in the center position.

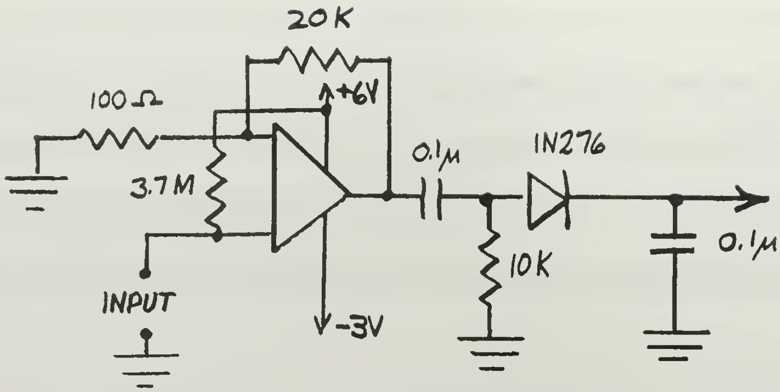


Figure 19. Amplifier, rectifier-holding circuit.

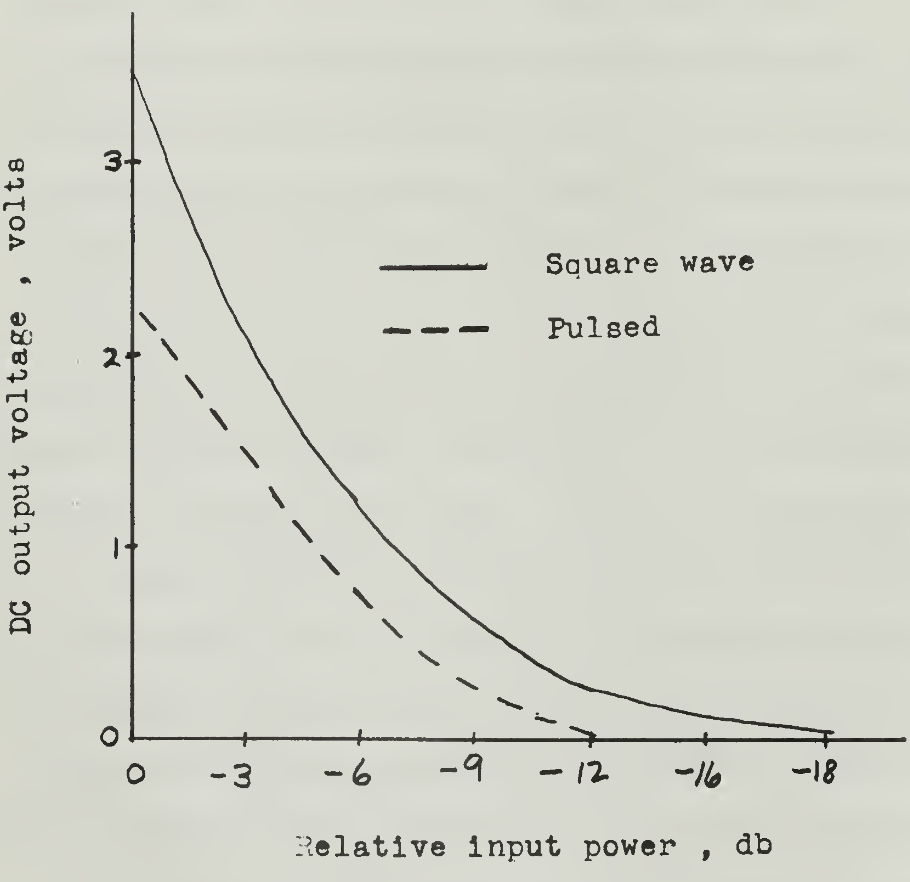


Figure 20. Holding circuit response.

0	0	0	0
0	0	0	0
0	0	.48	0
0	0	0	0

(a)

0	0	0	0
0	0	0	0
.21	0	.48	0
0	0	0	0

(b)

Figure 21. DC voltage response of image array (a) one source (b) two sources.

This was not done when data for Figure 16 was taken and the fifth and sixth rows fell on either side of the maximum. It is apparent from Figure 20 that additional feed elements would have had zero output.

5. Conclusion

The system may be improved in two major areas. The first is in resolution. The individual feed elements could be smaller so that closer spacing is possible, to recover the resolution of the system that was sacrificed because of the minimum spacing. However, there is a limit to the size reduction because the gain of each individual element will decrease as the size is reduced. The next step would be to increase the frequency of operation; however, as the frequency goes up the cost of diodes goes up and manufacturing tolerances of the reflector and feeds become very critical. Variable focusing may be desirable for very short range operation.

The second area of improvement is in the amplifier. A simple one stage amplifier is barely satisfactory and probably additional stages will be required for the amplifier to exhibit all the desired qualities. A further requirement for a useable system would be an amplifier with a logarithmic response, that is, lower gains for high input levels and increasing gain for lower signal levels to make the dc output voltage linear with respect to the input voltage.

An array of 30 x 30 is probably the minimum possible size to produce a useable image. Aperture blocking may not be a serious problem even for this size feed mosaic but, a simple, low cost amplifier must be designed in order that the system cost and complexity not be prohibitive since 900 separate channels would be required.

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APPENDIX A

The typical performance figures for the Fairchild μA702C integrated operational amplifier with $v^+ = 6v$ and $v^- = 3v$ are:

Input bias current	2.5 μA
Input impedance	40 KΩ
Input common-mode rejection	80 db
Open-loop voltage gain	700
Open-loop bandwidth	1 MHz
Output impedance	300 Ω
Maximum output swing	$\pm$ 2.7 v
Power input	17 mW
Input-referred positive-supply sensitivity	100 μv/v
Input-referred negative-supply sensitivity	200 μv/v

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13. ABSTRACT

An experimental investigation of microwave imaging using preformed beams is made at a frequency of 24 gigahertz (λ = 1.25 cm).

The apparatus consists of a 1.5 meter diameter parabolic reflector with a mosaic of detectors at the focal plane. The detector outputs are amplified and stored to provide a set of d.c. voltages, proportional to the energy received at points in the image plane, to be applied to an intensity modulated display.

Using microwave antenna and optical principles, the theory of image formation and resolution is discussed. The range capability is predicted by the radar range equation, using measured parameters.

Advantages of the system with respect to conventional scanning radar appear for fast moving objects at close range.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Microwave Imaging						
Preformed Beams						
Imaging						
Image Formation						
Detector Mosaic						
Azimuth-Elevation Presentation						
Scanning Radar						